Policy for Energy-Technology Innovation

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Introduction

The United States and the world face pressing economic, environmental, and security challenges arising from the energy sector, paramount among them providing the increased quantities of affordable energy needed to meet economic aspirations, limiting the political and economic vulnerabilities of heavy dependence on oil, and reducing the risk of unmanageable disruption of global climate by emissions of carbon dioxide from all fossil-fuel burning. Improving the technologies of energy supply and end-use is a prerequisite for surmounting these challenges in a timely and cost-effective way.

The United States ought to be the leader of the world in the energy-technology innovation that is needed. It has the largest economy, uses the most energy (and within that total the most oil), has made the largest cumulative contribution to the atmospheric buildup of fossil carbon dioxide that is the dominant driver of global climate change, has a large balance of payments stake in competitiveness in the global energy-technology market as well as a large stake in the worldwide economic and security benefits of meeting global energy needs in affordable and sustainable ways, and possesses by many measures the most capable scientific and engineering workforce in the world. The actual performance of this country in energy-technology innovation, however, has been falling short by almost every measure – in relation to the need, in relation to the opportunities, in relation to what other countries are

doing, and even in the simple-minded but still somewhat instructive measure of investment in energy-technology innovation in absolute terms and as a proportion of GDP, compared to the past.

Current U.S. federal government investments in energy research, development, and demonstration (ERD&D) are about the same in absolute terms as they were 25 years ago…and thus less than half as large as 25 years ago in relation to GDP. Japan has passed the United States in absolute magnitude of public expenditures for ERD&D and, with correction for purchasing power parity, China may soon do so. Private-sector ERD&D expenditures are harder to track, but this much is clear: the pace of improvement of key indicators of energy-sector performance (such as the ratios of energy use, oil use, and CO_2 emissions to real GDP) is far short, in the United States and worldwide, of what will be needed to surmount the major challenges; and, in such key sectors as renewable energy and energy end-use efficiency, leadership in innovation has been passing from the United States to Europe and Asia.

Public and private ERD&D expenditures are small in relation to the economic, environmental, and security stakes and even in relation to total national expenditures for energy itself. U.S. federal budget authority for basic energy sciences and energy-technology research, development, and demonstration combined was under $3 billion current dollars in FY2008 – an amount of money corresponding to about 2 cents per gallon on U.S. gasoline sales. The combination of state, local, and private-sector spending in these categories is probably 1 to 2 times the federal figure, hence no more than $6 billion per year. The U.S. total of $9 billion per year or less for ERD&D corresponds to less than one percent of the amount that the country was paying for energy at retail in the same period. For comparison, average R&D expenditures for all U.S. manufacturing sectors are around 4 percent of revenues, and some high-tech sectors such as drugs, software, and computer chips reach the range of 10-15 percent of revenues. Another instructive comparison is that the $9 billion upper estimate for annual public and private ERD&D expenditures in the United States corresponds to only about six days' worth of U.S. oil imports at $130 per barrel.

It might be supposed from such comparisons that increasing national investments in ERD&D should be an easy matter, but obviously it has not been. Fluctuations in ERD&D investments have accompanied oil-price shocks and other causes of varying enthusiasm and optimism about improving the menu of energy-technology options. But, despite a decades-long chorus of exhortation for more from the science-and-technology community and a more-or-less steady increase in the evidence about the economic, environmental, and

national-security perils of continuing reliance on the currently available options and incremental modifications of them, the overall state of U.S. ERD&D in the early years of the 21st century remains what it has long been – woefully inadequate in relation to the challenges and opportunities the sector presents.

Many explanations for the evident difficulty of strengthening public and private efforts in ERD&D have been offered and analyzed. These include: lack of sufficient private incentives and public and policy-maker political will for investing in addressing the externality and public-goods liabilities of the conventional energy-supply mainstays; the nature of energy as a commodity, thus subject to price fluctuations that impose large uncertainties on the returns to be expected from investment in innovation; the high capital cost and slow turnover time of typical energy facilities; the strong economies of scale in many energy-supply technologies, which mean that demonstration projects large enough to establish economic competitiveness (or the lack of it) for a new technology are very costly; the "chicken and egg" problem associated with the large investments in new infrastructure needed to make some of the new technologies effective at scale (hydrogen pipelines and filling stations, pipelines for CO_2 sequestration, additional transmission capacity for large-scale wind); the financial pressures on corporations to allocate resources to functions with more predictable benefits than RD&D for the short-term bottom line; and the inherent difficulty of answering the question, with respect to investment in innovation, of "How much is enough?"

In the United States in particular, these generic obstacles to increasing ERD&D efforts are compounded by a widespread belief that the Department of Energy is an especially dysfunctional government bureaucracy that has too many non-energy responsibilities and could not be trusted to spend increases in public funding for ERD&D in an effective manner; by the fact that federal ERD&D funding is in direct competition with politically more popular highway and water projects in the relevant Congressional appropriations subcommittees; and by strident debates among purported experts about whether such problems as climate change and overdependence on oil are really problems at all.

Whatever the relative responsibility of these and other factors for the mismatch between current levels of effort in energy-technology innovation and the needs for improved technologies imposed by the very real energy problems that the USA and the world currently face, what is clear is that the mismatch is not fixing itself and must therefore be seen as a major challenge for policy. And what is needed from policy, of course, is not just more

public resources and private incentives for energy-technology innovation, but improvement in the management and coordination of the efforts, including more and more effective use of partnerships (local-state-federal, university-industry-government, international, and combinations of these).

In the remainder of this essay we elaborate on the dimensions of this challenge and the available approaches for meeting it as follows:

- Section 2 expands on the nature of the main energy-related challenges faced by the United States, in the global context.
- Section 3 defines energy-technology innovation, discusses its indispensable role in addressing the challenges, and expands on the reasons for the inadequacies in the ETI efforts of the U.S. public and private sectors.
- Section 4 addresses the uncertainties and time-lags associated with reaping the benefits of ETI and derives from this discussion some conclusions about the importance and urgency of decisive government action in ETI policy.
- Section 5 describes the technology-push and market-pull ETI policy options that could be used to shape and accelerate ETI in the United States relative to what is be expected in the absence of such policies.

1 Pressing energy challenges

Energy is critical in today's world through its effect on the economic, environmental, and socio-political dimensions of human well-being alike.

- Economically, it is an indispensable ingredient of basic material well-being and economic growth; expenditures on it usually account for 7-10 percent of a country's GDP; it typically plays an even larger role in international trade and the associated balance of payments; its costs can powerfully affect economic competitiveness among regions and countries; and energy equipment is a major, global, high-technology market.
- Environmentally, the current technologies of energy supply are the dominant sources of many of the most dangerous and difficult environmental problems from the very local (indoor air pollution from burning biomass and coal in inefficient stoves in badly ventilated residences) to the regional (outdoor air pollution, water pollution, and acid rain) to the global (climate change driven largely by greenhouse gases from the fossil-fuel system).

- Politically, control of energy resources is a source of political as well as economic leverage and power; controlling or assuring access to such resources has been a source of military conflict and could be again; windfall energy revenues have been magnets in many places for corruption and have fuelled arms buildups and paid for fomenting and carrying out terrorism; and nuclear energy, while avoiding many of the environmental problems of fossil fuels, has the potential for misuse as a source of nuclear weapons.

The challenges arising from these interactions are many and mostly obvious.

1.1. Economic challenges

The fraction of GDP claimed by energy costs has been rising for the United States and most other countries, driven above all by the rising cost of oil and also by electricity costs going up in consequence of both fuel-cost increases and rapid escalation in the cost of building electric power plants. When energy costs increase too much or too fast, of course, the result is inflation, recession, and sacrifice, above all for the poorest.

The United States, in particular, is a poster child for heavy oil dependence and the economic vulnerability that this entails. The world's largest oil guzzler, the United States consumed 20.7 million barrels of petroleum per day in 2007, deriving 40 percent of national primary energy from this source and importing almost 60 percent of it (EIA 2008d). In 2007 the value of the energy-related petroleum imports[1] in the United States was $319 billion (USCB 2008), amounting to 16 percent of the value of all U.S. imports and 2.3 percent of GDP. It is almost superfluous to add that some of the largest exporters of oil to the United States are in the world's most unstable regions.[2]

It is important to note, moreover, that with oil prices set in a global market the degree of a country's economic vulnerability is proportional to its total oil dependence, not just to its import dependence – the economy is hit with the market price increase on every barrel (although the degree of import dependence of course affects who gets the money). The manifest advantages of reducing U.S. dependence on oil and the imported fraction of it alike notwithstanding, the country is not on a path to get there: the reference forecast of the US Energy Information Agency anticipates U.S. demand for liquid fuels 10 percent higher in 2030 than it is today, while domestic and imports are about the same (EIA 2008a). In this

[1] The category of energy-related petroleum products includes crude oil, petroleum preparations, and liquefied propane and butane gas. About 75 percent of the total value of the energy-related products in 2007 corresponded to crude oil.

[2] In 2007 about 21 percent of all crude oil imports into the United States came from the Persian Gulf, and another 21 percent from Lybia and Nigeria.

EIA. 2008d. Monthly Energy Review June 2008. *Energy Information Administration.*).

forecast, the growth in liquid fuels is made possible by increases in biofuels and coal-to-liquids. Some other analysts expect domestic oil production to be declining in this period, as it has done at an average annual rate of 2 percent per year since 1970. Elsewhere in the world, particularly in the developing countries, oil demand and oil imports are expected to grow rapidly (IEA 2007b).

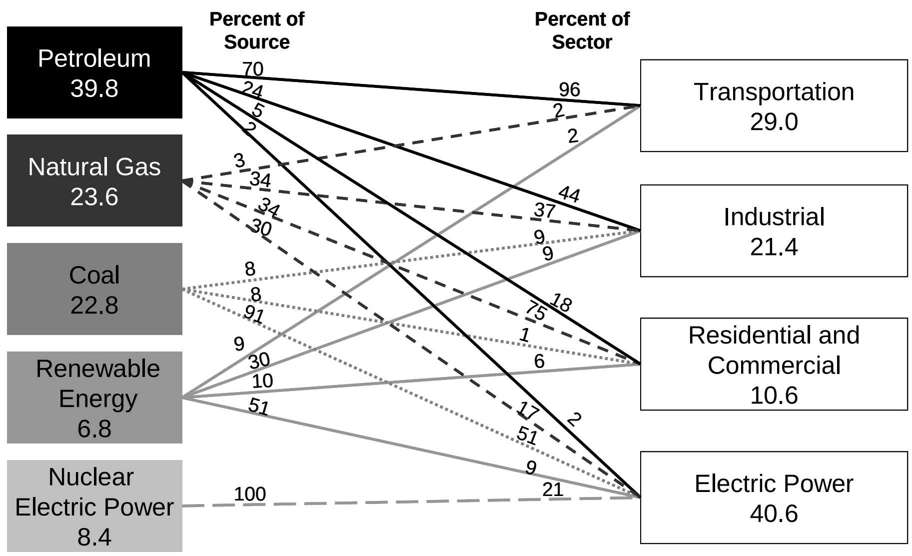

Figure 1: U.S. primary energy consumption by source and sector in 2007 in quadrillion Btu (EIA 2008b).

A second economic challenge is that U.S. companies are at risk of arriving late to the global market for advanced energy technologies. In a world where energy needs could well be more than 50 percent higher than today in 2030 (IEA 2007b), the United States could lose substantial commercial opportunities if it does not manage to capture a significant share of the market in energy-supply technologies (recently estimated at $400 billion per year and growing (NCEP 2004a). Although the United States has some of the world's best research groups and laboratories, its industrial sector is currently not leading the world in the manufacture and deployment of most of the advanced energy technologies destined to claim a growing share of this market. For example:

- Eight of the top ten wind turbine manufacturers are European, and in 2005 they accounted for 72 percent of the global market, which was worth $18 billion in 2006 (EWEA 2007).

- None of the top five global producers of photovoltaics were based in the United States (REN21 2008).[3] The PV market was worth $12.9 billion in 2007 (Moran 2007).
- Of the 35 new nuclear plants that were under construction as of July 2008 (IAEA 2008), none were based in the United States, and the only Generation III reactors in the world are located in Japan (WNA 2008).[4]
- Currently two Japanese producers (Panasonic EV Energy and Sanyo) share over 85 percent of the world's market of batteries for hybrid electric vehicles (HEV), which use nickel metal hydride (NiMH) technology. This market was estimated to be worth $600 million in 2006 and is expected to grow up to $2.3 billion by 2013 (Anderman 2007).[5]

Of course, market share in advanced energy technologies is not just a matter of balance of payments and economic growth *per se*; it is a matter of high-quality jobs for Americans.

1.2. Environmental challenges

Global climate change is increasingly recognized as the most dangerous and probably the most intractable of all of the environmental impacts of human activity (Holdren 2006). There is no longer any reasonable doubt that the Earth's climate is changing at a pace that is highly unusual against the backdrop of natural climatic variations (IPCC 2007a). There is also widespread scientific agreement that the accumulation of anthropogenic GHGs resulting primarily from the combustion of fossil fuels is the main cause of these unusual climate changes,[6] and that they are already having significant impacts on ecosystems (Parmesan 2003) and, directly as well as through those ecosystem impacts, on human well-being (IPCC 2007a; UNEP 2005; UNSEG 2007).

Until very recently, the United States was the world's largest CO_2 emitter, with about 22 percent of the global total; but China took over first place with a similar percentage in 2007.

[3] The top five global producers of PV cells were: Sharp (Japan), Q-cells (Germany), Kyocera (Japan), Suntech (China), and Sanyo (Japan)

[4] They are advanced boiling water reactors (ABWRs) and were built by a joint venture of GE, Hitachi, and Toshiba.

[5] Currently about one dozen companies from Japan, South Korea and the United States are intending to compete on the market for advanced Li-ion batteries.

[6] In 2004 CO_2 emitted from the use of fossil fuels made up 56.6 percent of total GHG emissions, measured in CO_2-equivalent.

IPCC. 2007b. Report of Working Group II: Summary for Policy Makers. *Intergovernmental Panel on Climate Change, Fourth Assessment Report*.).

The United States has been responsible for 28 percent of the cumulative global CO_2 emissions from 1751-2004 (Raupach 2007) and remains the world's largest per capita emitter.

Unless the world takes sufficient action in greenhouse-gas emissions reductions to achieve a leveling off of emissions by about 2020, followed by a decline to something like 50 percent of the 1990 level by 2050 and continuing reductions thereafter, it will probably not be possible to limit the global-average surface temperature increase to less than 2 degrees C compared to 1900. (The increase to 2005 was about 0.8 degrees C, but the ultimate equilibrium value associated with atmospheric concentrations of greenhouse gases and particulate matter in that year would be a further 0.5 degrees C higher. Temperature increases lag behind concentration increases because of the thermal inertia of the oceans.)

Given the extent of changes in climatic patterns – and the associated damages to ecosystems and human well-being – already being experienced at only 0.8 degrees C above the 1900 level, it is a virtual certainty that success in stopping at 2 degrees C would not be enough to prevent substantial further harm, including in all probability further intensification of floods, droughts, heat waves, wildfires, and severe tropical storms; accelerated sea-level rise: decreased agricultural productivity in many regions; increased geographic range of tropical diseases; and more (IPCC 2007b). It is nonetheless very worthwhile to try to avoid even larger increases (as the European Union formally agreed already in 2002 when it endorsed staying below 2 degrees C as a target or the world), because there is considerable evidence that the possibility of crossing a threshold or "tipping point" into truly catastrophic, wholly unmanageable climatic disruption increases rapidly for temperature increases larger than that (UNSEG 2007).

A large part of the effort needed to bend down the trajectory of global emissions below business as usual in the next few years, as needed if it is to level off by 2020 and start an absolute decline thereafter, will obviously need to rely on technologies that are already available commercially or very close to it. There is no way for an enhanced effort at energy-technology innovation to have a large impact that quickly. But achieving the steadily larger reductions needed over time in order to stay on a trajectory to stabilize concentrations at a level that might hold the temperature increase below 2 degrees C will require major improvements in low- and no-emission energy-supply technologies and super-efficient energy-end-use technologies if those reductions are to be achieved without great economic sacrifice and perhaps other unwanted impacts.

Although there are other serious environmental issues besides climate change linked to energy resource extraction, processing, conversion, transport, and consumption – such as land degradation, water pollution, conventional air pollution, acid rain, depletion of aquifers and stream flow[7] and the impacts of the energy infrastructure on natural ecosystems ((Hightower 2008; UNDP 2000) – the climate-change challenge is by far the most demanding environmental driver of the need for increased ETI (PCAST 1997).

1.3. International security challenge

The economic and international-security dimensions of the U.S. energy predicament are interconnected through "the oil problem": the larger is U.S. economic vulnerability to oil supply disruptions and/or price shocks, the more likely it is that this country will resort to military action to try to prevent or terminate such conditions and the less freedom of action it will have to pursue other foreign-policy goals, including its anti-terrorism agenda (Holdren 2006). Oil-supply disruptions can be created not only by supplier states, moreover, but by terrorist action, and in either case cascading international-security consequences are a real possibility. [8] Instead of reducing foreign-policy liabilities, moreover, the current tendencies in U.S. and world energy supply are exacerbating them. For example, natural gas is increasingly becoming a global commodity of which more and more is being supplied from regions that are either politically unstable or inclined to use supply restrictions as a political weapon.

The other major energy-related international-security challenge is how to make expanded use of zero-carbon electricity from nuclear power – which to have much effect on the climate problem would need to happen not just in the United States but in many countries around the world -- without accelerating the spread of nuclear weapons and increasing the risks from nuclear terrorism. The United States has 104 working power reactors with a capacity of 100 GWe, generating almost 20 percent of the country's electricity. The world has over power 400 reactors totalling some 380 GWe of capacity and supplying about a sixth of global electricity. But if nuclear energy is to generate as much as a third of the doubled world electricity demand that is likely by 2050 or sooner, over 1500 GWe of nuclear capacity will be required. A considerable part of the increase would

[7] U.S. energy production accounted for 39 percent of fresh water withdrawals in the year 2000.

[8] In November 2007, a group of former top government officials gathered to "play" the Oil Shockwave Simulation, which was aimed at highlighting thedesigned to discover weaknesses in the United .S.tates energy policyies. They found that under the current policies, if oil supply was constrained as a result of a by terrorist actiongroups, some of the plausible consequences would be: a war in Iranq, gasoline rationing at $5 a gallon, a military draft, and double-digit inflation and unemployment
Broder, John. M. 2007. A War Game Supposes Scarce and Risky Oil. *The New York Times*.).

necessarily be in parts of the world that are of proliferation concern, or that plan to reprocess spent nuclear fuel (and thereby create weapon-usable plutonium), or that are even more at risk from terrorists than the United States, or all of these. If increases in nuclear energy of the indicated magnitude are to achieved and sustained without disaster, more attention will need to be devoted not just to improving the technology of nuclear energy in ways that reduce its vulnerability to terrorist attack or misuse for nuclear weaponry, but also to improving management and international oversight to these ends (MIT 2003; NCEP 2004a).

1.4. Tensions among the challenges

There are obvious interactions and often tensions among the economic, environmental, and security challenges associated with energy. One involves the potential security liabilities of expanding nuclear energy in order to help address the climate challenge, as just described.

Another is the set of tensions among the goals of ensuring the reliability and affordability of transport fuels and minimizing greenhouse gas (GHG) emissions. The United States could try to increase the reliable supply of energy for transport by increasing domestic production of conventional oil and natural gas (usable in vehicles as compressed natural gas – CNG); encouraging increased production of unconventional oil (e.g. oil shales and tar sands),; producing synthetic fuels from coal and biomass; increasing the production of biofuels; increasing electricity production from coal, nuclear, wind, or solar energy in order to charge plug-in hybrid or all-electric vehicles; and increasing the efficiency of liquid-fuelled transport technologies in ways other than the use of hybrids With the exception of the efficiency options and expanded use of nuclear, wind, and solar energy, however, all of the rest of these options would perpetuate CO_2 emissions from the transport sector and many would increase them unless equipped with CO_2 capture and sequestration technologies that are not yet available.

2 Need for energy-technology innovation

2.1. Energy-technology innovation is essential to address the energy challenges

Energy-technology innovation, or ETI, is the set of processes leading to new or improved energy technologies that can augment energy resources, enhance the quality of

energy services; and reduce the economic, environmental or political costs associated with energy supply and use (Gallagher 2006). Like all types of technology innovation, ETI is characterized by the research, development, demonstration, and deployment (RD3) phases, and the presence of multiple dynamic feedbacks between the different stages.

ETI is essential to mitigate energy-related economic liabilities because it will allow the United States to decrease its oil and natural gas dependence by: improving energy efficiency in vehicles, electricity production, industrial processes, and building technology; finding ways to avoid and/or replace the use of oil for transportation – which consumes 70 percent of the petroleum in the United States (EIA 2008b) – through the development of entirely new transportation systems (e.g. plug-in electric vehicles, or fuel cells) and/or the production of liquid fuels from other domestic resources; developing and integrating domestic and/or renewable electric power sources; and creating new building blocks for the chemicals industry from other sources, such as coal or biomass.

ETI is also crucial to ensuring that the United States profits from the increasingly substantial business opportunities in the energy-technology sector. In today's global economy, where the comparative advantage of high-cost countries lies increasingly in knowledge-based innovation activities (Audretsch 2006), the United States must ensure that it is the technological leader in the increasingly knowledge-driven energy sector.

There is now agreement that mitigating CO_2 emissions will be costly,[9] and that ETI plays a key role (if not *the* most important one) in reducing the costs of mitigating emissions.[10] Advanced energy technologies – which would result from an expanded and coordinated ETI effort – have the potential to decrease worldwide costs of achieving CO_2 stabilization at 550 ppm by the end of the 21st century by a factor of 2.5 (Edmonds 2004).

Through the development of improved nuclear reactor concepts, and nuclear waste disposal and reprocessing technologies, ETI can help the United States maintain its leverage in global discussions of nuclear technology standardization, reduce the risks of terrorist attacks on nuclear power plants, mitigate proliferation concerns from stolen plutonium, and ease the demand for permanent storage sites for spent fuel. In addition, by increasing its

[9] MIT used their EPPA model to estimate the welfare (GDP) costs of various cap-and-trade proposals aimed at reducing emissions in the United States consistent with global stabilization scenarios corresponding to 450 ppm. Their modelling results indicated that GDP losses could be between 0.5-1.8 percent
Sergey Paltsev, John M. Reilly, Henry D. Jacoby, Angelo C. Gurgel, Gilbert E. Metcalf, Andrei P. Sokolov, Jennifer F. Holak. 2007. Assessment of U.S. Cap-and-Trade Proposals. *MIT Joint Program on the Science and Policy of Global Change* 146:53.).

[10] The reduction of overall energy consumption by changing people's habits and lifestyles – by inducing or convincing people to use public transport, buy energy efficient appliances, turn their lights off, purchase less dispensable items, etc – can simultaneously reduce the United States dependence on foreign oil, and its GHG emissions.

efforts to find proliferation-resistant, waste-reprocessing technologies, and long-term solutions to waste disposal, the United States could reduce the chances that more countries will install non-proliferation-resistant nuclear facilities.[11]

Because of the multiple and often conflicting energy challenges, there is no single technology or technology cluster that can mitigate all energy-related risks. In fact, reliance on one set of technologies can create even more difficulties. We have already mentioned the example of attempting to substitute oil with biofuels, which would impose significant costs on the world's ecosystems, and on food consumers in the United States and (perhaps more critically) abroad. The phrase "there is no silver bullet" has been widely used over the past decade to describe this phenomenon. ETI policies must be formulated to accelerate the development and deployment of a wide portfolio of technologies to *tackle all challenges simultaneously*.

2.2. Why has the U.S. ETI effort been inadequate?

Given the ability of ETI to simultaneously and significantly address the pressing economic, environmental, and international-security challenges faced by the United States, one may wonder why the country is relying on this less-than-sub-optimal set of energy technologies, and why policy makers have not acted sooner. There are of course several reasons for this.

- The lack of political will, and the subsequent lack of incentives for the private sector to engage in ETI, has contributed to insufficient public and private sector efforts to address the public good (e.g. national defense, and atmosphere) and externality (e.g. local pollution, global warming, and knowledge spillovers[12]) market failures associated with conventional energy technologies.
- In addition to the public good and externality market failures, industry structure characteristics also contribute to sub-optimal private investment in ERD&D. First, it is often necessary to invest a critical mass to see the private returns to innovation, and thus, small companies generally underinvest in ETI. And second, uncertainties and long-term time-scales characterizing the technology innovation enterprise, cause shareholder-focussed firms to only invest on programs offering short-term and less risky returns, resulting in underinvestment also from larger firms.

[11] Currently France, Japan, the United Kingdom, and Russia are the only countries with spent fuel reprocessing facilities.

[12] Spillovers are positive externalities from innovation which cannot be completely captured by the firm making the investments.

- Energy is a commodity, and as such, it is subject to price fluctuations and uncertainties on the returns to be expected from investments in innovation. Thus in periods of low energy prices – like the 1980s and 1990s, when the world enjoyed low oil and natural gas prices – the public and the private sectors have even less incentives to invest in things like energy efficiency, as they have no certainty about when they will recover the investment.
- Traditional energy supply facilities have slow turnover times and high capital costs. Both of those attributes represent barriers to the deployment of new technologies.
- Economies of scale are very important in energy technologies. As a result, demonstration projects, which are aimed at scaling up and testing a technology to make improvements, are very expensive. This expenditure is hard to justify from the point of view of a private sector decision maker.
- Similarly, for some new technologies to be deployed in a cost-effective manner (e.g. electric vehicles, fuel cell vehicles, large scale wind or solar electricity) it is necessary to have an underlying infrastructure, such as additional transmission and distribution lines, hydrogen pipelines and fueling stations, energy storage facilities, and CO_2 pipelines and storage equipment. But these "enabling technologies" are themselves expensive, and hard to finance without some certainty about the size of the market that will be using the infrastructure.
- The belief that the market is more efficient at commercializing energy technologies, and that the government should reduce its involvement in funding energy research, development, and demonstration (ERD&D) has been one of the drivers of the decline in federal funding for ERD&D in the United States.[13]
- An effective institutional structure able to advocate for and implement a sounder ETI strategy is lacking. This institutional failure, together with the short-term nature of the

[13] The advocates of this "let the market do it" argument were partly fuelled by the failure of several DOE-funded large-scale energy-technology demonstration projects in the 1970s and the 1980s. The Clinch River Breeder Reactor (CRBR), and the Synthetic Fuels Corporation (SFC) are the two most significative failed commercialization projects carried out by DOE. The failures of the CRBR project (which cost $1.6 billion in 1996$)
GAO. 1996. Department of Energy: Opportunity to Improve Management of Major System Acquisitions. *U.S. General Accounting Office*:19.), and the SFC (in which several billion dollars were spent), have been adscribed to three main causes: (a) the overly optimistic engineering estimates of cost and technological readiness, (b) the focus on performance and not on costs, and (c) the fact that the project results were so dependent on DOE business practices that they were not credible for the private sector
Ogden, Peter, Podesta, John, Deutch, John. 2008. A New Strategy to Spur Energy Innovation. *Issues in Science and Technology* (Winter).

federal budget process, has made it difficult to create coordinated long-term energy policy legislations.

- Difficulties in determining how many resources should be devoted to ETI and how they should be spent further complicate matters and prevent policy makers from taking action.

Although the aforementioned "causes" of the inadequate ETI effort – which apply not only to the United States but in most cases also to the rest of the world – have been acknowledged for many years, remarkably little has been done to change the situation, especially at the federal level.

3 Acting in time is crucial

The United States has reached a point where postponing action – either out of desire to know more about climate change, or out of faith that new technologies will naturally come online and reduce the costs of dealing with the U.S. energy challenges – is no longer an option. A concerted ETI effort must be set in motion over the next two years if the United States is to maintain its role as a flourishing and competitive economy, put the world in a path to prevent the evolution of the global warming phenomenon into a crisis of unmanageable consequences, and minimize the chances of fossil fuel or nuclear-energy related conflicts. The window of opportunity is indeed very small.

3.1. Economic time-sensitivities

There are several economic consequences of not taking immediate action to strengthen the U.S. ETI system.

Growing global demand for energy and for low-carbon technologies is creating a large market for energy-technology suppliers. About $22 trillion will have to be invested to meet the world's energy demand in 2030 (IEA 2007b). It has been estimated that global public and private sector expenditures in clean energy have increased by 60 percent from 2006 to $148 billion in 2007 (UNEP 2008). Yearly renewable energy investment is expected to triple by 2012 to reach $450 billion, and quadruple by 2020 to reach $600 billion. But with this growth in market opportunities, international competition is also growing. Of the total $118 billion spent in sustainable energy[14] by venture capital deals, private equity, public

[14] The UNEP - New Energy Finance study defines sustainable energy as: all biomass, geothermal and wind generation projects of more than 1 MW, all hydro projects between 0.5 and 50 MW, all solar projects of more

markets, and asset finance, 47 percent went to Europe, 23 percent to the United States and 22 percent to developing countries – China, India and Brazil alone received 17 percent. Although the United States and Europe each spent about half of the total $9.8 billion of investment in early-stage financing (i.e. venture capital and private equity investments), Europe is leading the world in deployment, and the share of total investments captured by emerging economies is growing very rapidly.[15]

Industrialized economies are determined to make the most of the energy business. In 2005 Japan released its Strategic Technology Roadmap in Energy Field, identifying its short-, medium-, and long-term energy R&D needs (METI 2005), and in January 2008 it announced that it will spend $30 billion over the next 5 years in ERD&D, and $10 billion assisting developing countries in the deployment of low-carbon technologies (Fukuda 2008). The European Union has also embarked on a large effort to put ETI at the forefront of its policy agenda. Its Strategic Energy Technology Plan (SET-Plan), which was released in November 2007, aims to support the EU's ambitious renewable energy goals,[16] and complement its Emissions Trading Scheme (ETS) system. The SET-Plan has several components which include: the creation of a Steering Group on Strategic Energy Technologies and an European Energy Technology Information System, an increase in EU-wide funding for ETI, and the creation of the European Industrial Initiatives (EU 2007b). The SET-Plan is still in a consensus-building state, and it is very likely that some action will be taken. Finally, developing countries are not only using more energy, but also playing an increasing role in ETI and its markets.

Although the system is too complex to predict the exact fraction of the market – of the estimated $600 billion per year – that U.S. firms would be able to capture if the U.S. government changed course, it seems reasonable to assume that the difference between action and inaction will be at least in the range of tens of billions of dollars.

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than 0.3MW, all marine energy projects, all biofuels projects with a capacity of 1 million liters or more per year, and all energy efficiency projects that involve financial investors. The $118 billion figure excludes governmental and corporate RD&D and small-scale projects (approximately $36 billion) and reinvestment ($5.3 billion).

[15] The large market opportunities in energy technologies are now being captured by many European and Asian firms: e.g. only one of the top 7 wind turbine manufacturers in terms of production is American, none of the top 5 PV cell manufacturers, which produce over half of the world's PV cells, are American, and the hybrid electric vehicle NiMH battery business is controlled by Sanyo and Panasonic, both from Japan.

[16] In 2007 the EU committed to achieving the following goals by 2020: reducing its GHG emissions by 20 percent, increasing energy efficiency by 20 percent, increasing the share of renewables in overall EU energy consumption from 8.5 percent to 20 percent, and increasing the biofuel component of vehicle fuels up to 10 percent.

Deploying advanced energy technologies in the United States could promote the creation of high-quality jobs.[17] For example, adopting a 20 percent renewable energy portfolio standard (RPS) could create 100,000 to 200,000 more jobs[18] than using a 50-50 mixture of natural gas and coal to meet that 20 percent of energy demand (Kammen 2004). This difference is also time-sensitive. The longer it takes to deploy renewable electricity technologies, the more conventional power plants that will have to be built to meet demand. Conventional power plants have long lifetimes, which means that those renewable-energy jobs would be effectively lost.

The economic dangers associated with the U.S. dependence on oil are large.[19] Last year, when the average cost of a barrel of oil was about half of what it cost in July 2008, the United States spent over $260 billion in crude oil imports.[20] The economic cost of oil-price shocks has been widely investigated. A sustained $10 increase in oil prices has been estimated to result in a decrease in the U.S. GDP of 0.3 percent (IEA 2004), and a conservative estimate is that a 10 percent oil-price shock would lead to a 0.10-0.15 percent decrease in the U.S. GDP within four to six quarters (Rogoff 2006),[21,22] The sooner the United States transitions away from oil, the lower the overall wealth transfer to oil exporting countries, and the lower the costs associated with potential supply disruptions.

The above estimates of the economic impacts of the U.S. oil dependence do not account for the costs of "peak oil" taking place. Since 1956, when the geologist M. King Hubbert correctly predicted that the U.S. oil production capacity would peak in the 1970s, there has been much speculation regarding when world capacity would peak because as peak oil is approached, liquid fuel prices and volatility are expected to increase dramatically, and timely mitigation will be essential to reduce its economic, social, and political costs (Hirsch

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[17] The creation of high-quality jobs is important at this point in time. Between 1995 and 2005 the United States lost over 3 million manufacturing jobs, and nearly all of the loss took place between 2000 and 2005 Friedhoff, Alec. 2006. Bearing the Brunt: Manufacturing Job Loss in the Great Lakes Region, 1995-2005. *Brookings Institution* (July).. This number is likely to have grown over the past few years.

[18] These jobs include fuel procurement, operation and maintenance, and manufacture and installation.

[19] Note that this is despite of the fact that it is argued that United States is somewhat less vulnerable to oil price shocks that it was a couple of decades ago, possibly due to a combination of improved monetary policy, increased concentration of impacts around one sector, more flexible labor markets, and a lack of concurrent adverse shocks
Rogoff, Kenneth. 2006. Oil and the Global Economy. *New Economic School of Russia*..

[20] This value was calculated multiplying the 2007 average spot price at the West Texas Intermediate of $72 per barrel, by 3.7 billion barrels imported in 2007
EIA. 2008b. Energy Basics 101. *U.S. Energy Information Agency, Office of Energy Statistics*.).

[21] Rogoff *et al.* point out that some authors can "rationalize effects that are an order of magnitude larger."

[22] The total economic costs of the U.S. oil dependence between 1970 and 2005, according to the Oak Ridge National Lab, added up to between $2 and $6 trillion dollars in year 2000$
Greene, David L., Ahmad, Sanjana. 2005. Costs of U.S. Oil Dependence: 2005 Update. *Oak Ridge National Laboratory*.

2005). Although the date of peak oil cannot be determined with certainty, most recent estimates indicate that peak oil might have already been reached, or that it might be reached in the not too distant future.[23] Given that the large-scale implementation of alternative supply and end-use options will take decades, and that the costs of approaching peak oil with an unprepared economy are likely to be very large, risk management requires the implementation of mitigation well before peaking (Hirsch 2005).

3.2. Environmental time-sensitivities

Accelerating the development and deployment of low-carbon energy supply and end-use technologies is also (if not more) extremely time-sensitive from a climate change perspective.

Energy infrastructures have long lifetimes – ranging from 10-15 years for cars, to 20-60 years for energy supply facilities and manufacturing plants, to much longer for buildings – and therefore most of the energy infrastructures that will be built in the next decade will still be in use in 2050. Unless low-carbon technologies are deployed over the next two decades, the United States and the world will be locking-in enough carbon emissions to push the Earth's climate beyond what prudence requires.[24] The potential for *carbon lock-in* is particularly alarming in the use of fossil fuels in the power sector, and oil in the transportation sector. If the world's nations build the fossil power plants that are projected to be built before 2030 without CCS, these plants will have lifetime CO_2 emissions comparable to the cumulative emissions from the combustion of fossil fuels between 1751 and 2002 (Socolow 2005).[25] Most importantly, the estimated 735 Gt of CO_2 that would be emitted from these new plants alone would account for 47 percent of the total CO_2 budget from 2005 and 2100 for a 450 ppm CO_2 stabilization level (Edmonds 2007a). What this means is that if these fossil fuel power plants are built, it will be nearly impossible for the world to stabilize GHG concentrations in the atmosphere at 450 ppm, and perhaps even at 550 ppm, unless it resorts to climate-engineering: e.g., sucking CO_2 out of the atmosphere

[23] Peak-oil dates in the literature range between 2006-2007 to after 2025.

[24] The perpetuation of fossil fuel-based energy infrastructures in spite of their environmental costs and apparent existence of remedies, known as "carbon lock-in," can be thought of as being driven by technological and institutional inertia—once led down a particular technology path, the barriers to switching may be prohibitive.
Jaffe, A. B., Newell, R. G., Stavins, R. N. 2003. *Innovation Policy and the Economy. Chapter 2: Technology Policy for Energy and the Environment*, *The MIT Press for the National Bureau of Economic Research*. Cambridge, MA,
Unruh, Gregory C. 2000. Understanding carbon lock-in. *Energy Policy* 28:817-830.).

[25] These calculations were based on baseline scenario projections by the IEA World Energy Outlook in 2004. Socolow's calculations assumed that the lifetimes of natural gas, oil, and coal power plants were respectively 20, 40, and 60 years.

and storing it; or reflecting sunlight back into space by seeding the atmosphere with sulfur particles, deploying mirrors into space, or spraying aluminium particles into the troposphere. However, these options are not only merely theoretical and potentially dangerous, but also far more expensive than mitigating CO_2 emissions with technologies available today.

It is also urgent to transition the transportation sector away from oil because demand for oil and even less environmentally-friendly fuels is increasing. For example, China – which has an oil demand that is projected to increase by 150 percent between 2005 and 2030 (IEA 2007b), and an oil production expected to peak around 2015 (WRI 2008) – has already started to demonstrate coal-to-liquids technologies to help meet its transportation needs.[26] The United States must lead by example with policies to catalyze its transition to low-carbon technologies, and engage in international cooperation to encourage large industrializing countries to start in a low-carbon path to avoid irreversible carbon lock-ins.

Developing and deploying low-carbon energy systems globally is also essential because better energy technologies are needed if the costs of mitigating GHG emissions are to be controlled. The cost savings of limiting the likely global average temperature rise to 2 degree C with advanced energy technologies[27] could be in the range of tens of trillions of 2005$ (Edmonds 2007b) but the scale of the technology challenge to achieve stabilization is enormous, and thus, the sooner this deployment starts, the easier it will be to achieve the required scale within the right time frame.[28]

Finally, the sooner the U.S. government acts, the lower the costs of the climate change damages. Although it is inherently difficult to make economic forecasts stretching 100 years, it is important to have an idea of the order of magnitude of the potential costs of inaction. The German Institute for Economic Research (Deutches Institut für Wirtschaftsforschung, DIW) estimated that the annual costs of not mitigating emissions and reaching a global average temperature increase of 4 degree C above pre-industrial levels by 2100 – scenario which could well be in the lower bound of the expected temperature rises if aggressive policies to limit worldwide emissions are not put in place – could to reach $20 trillion in 2002$ by 2100, or 6-8 percent of global economic output (Kemfert 2005). This order of magnitude agrees with estimates by Cambridge University's PAGE model (Watkiss

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[26] Synthetic fuels produced from coal without CCS capabilities result in twice as much CO_2 emitted per unit of energy as gasoline.

[27] Their analysis advanced energy technology scenarios included the large-scale deployment of CCS, biotechnology, hydrogen, nuclear, solar and wind, and end-use energy technologies.

[28] The case of CCS technologies will serve to illustrate the point about scale: if CCS is to significantly contribute to climate change mitigation, its deployment must be scaled up by several orders of magnitude—from 1 million tons of carbon sequestered underground worldwide in the year 2000, to 70 million tons per year in 2020, and 6,000 million tons per year by 2095.

2005). Both studies found that the costs of the damages would be reduced by over one half if immediate policy action was taken (Ackerman 2006).[29]

3.3. International security time-sensitivities

The benefits or avoided costs of early action to mitigate energy-related, international-security risks are even harder to quantify than those associated with economic and environmental challenges, but the probability of their occurrence is likely to increase with time, unless appropriate ETI policies are put in place in the very short term.

Global demand for oil and natural gas is projected to grow faster than production, thereby increasing international tensions. The probability of and damages associated with terrorist attacks to energy infrastructures, and the number and size of foreign-policy liabilities associated with the U.S. dependence on oil and natural gas is likely to grow with time unless the United States changes its course.

Nuclear energy has the potential to contribute to help the United States and other countries meet their energy needs while reducing GHG emissions. To make a significant contribution to the world's energy security and environmental challenges, however, nuclear energy would need to increase its share of worldwide electricity production from 1/6 in 2000 to 1/3 in 2100, which involves growing nuclear energy from 350 GW to about 3,500 GW (Holdren 2005), with most of this capacity increase taking place in industrializing countries. An expansion of this kind without an acceleration of ETI, the U.S. participation in international cooperations in nuclear technology and non-proliferation, and an expanded role and funding for the International Atomic Energy Agency (IAEA), would result in an increase in the risk of a serious major accident,[30] a terrorist nuclear bomb,[31] and a nuclear sabotage[32] (Bunn 2008).

4 Policy tools for energy-technology innovation & recommendations

Energy-technology innovation policies are those government actions which are aimed at shaping the direction of energy-technology innovation, and the time when innovations take place. As such, policies for energy-technology innovation include policies

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[29] The costs included in the studies available are not exhaustive, and do not include non-market damages and socio-political implications of climate change
Watkiss, Paul. 2006. Climate change: the cost of inaction and the cost of adaptation. *European Environment Agency*.)

[30] More reactors means more risk unless per reactor risks are reduced.

[31] If spent fuel reprocessing expands with technologies available today.

[32] Again, more reactors in more places translates into more chances for security mistakes, or higher chances of a successful sabotage.

that fund or subsidise RD&D activities aimed at advancing or creating energy technologies; promote the education of more and better-trained scientists and engineers; set standards of performance for energy supply and end-use technologies; encourage the deployment of advanced energy technologies through tax or other policies; or place quantity restrictions or taxes on the emissions of certain substances. This wide range of ETI policies is not exhaustive, and it illustrates the complexity of influencing and steering a country's energy-technology base.

The United States needs to set-up, improve, coordinate, and scale-up its ETI policies. Both *technology-push* and *market-pull* ETI polices will be essential to address its pressing energy security, economic, and environmental challenges (see Figure 2). On the technology-push side, we will consider federal policies which: (a) fund ERD&D activities and directly encourage an increased participation of the private sector and an increased cooperation between the United States and other countries; and (b) increase the quality and the quantity of the ETI workforce. On the market-pull side we will focus on policies which: (a) encourage the early deployment and widespread diffusion of new energy technologies through direct expenditures, tax-related expenditures, or financial support; (b) spur ETI by setting technology performance standards; and (c) impose climate regulations to encourage ETI and steer it in a direction that correctly accounts for the negative environmental externalities of GHG emissions.

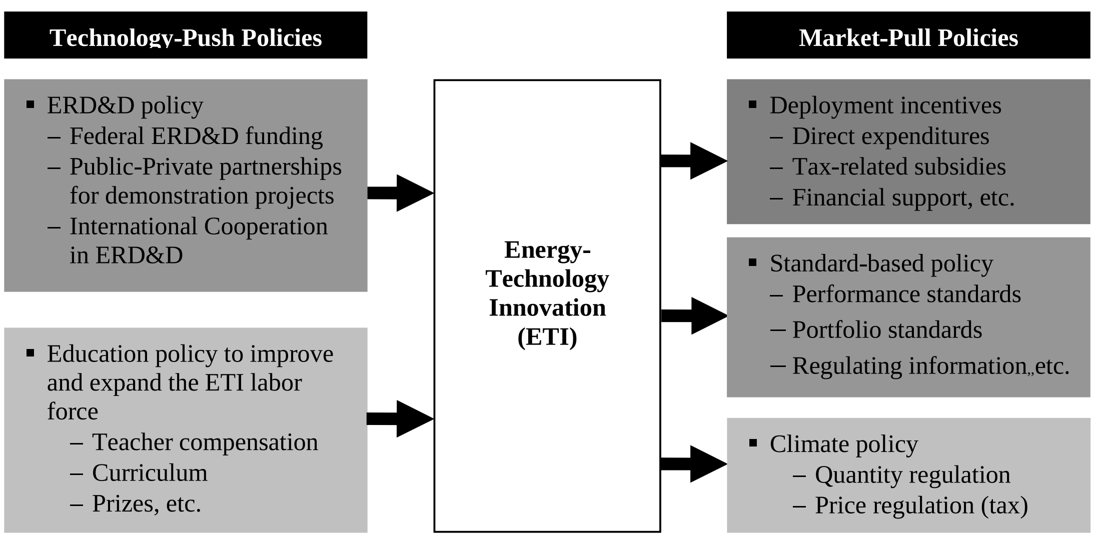

Figure 2: Schematic of the considered types of technology-push and market-pull policies that affect energy-technology innovation.

4.1. Energy research, development, and demonstration policy

4.1.1 Public sector

As the U.S. President's Committeee of Advisors in Science and Technology (PCAST) put it "research and development is the only systematic means for creating the needed technical improvements and therefore, is a necessary (although not always sufficient) condition for improving the energy systems that are actually deployed" (PCAST 1997). In spite of the clarity of this concept, the United States has seen its public and private sector funding in ERD&D decrease significantly over the past couple of decades.

Since its creation by President Carter in 1977, the Department of Energy (DOE) has been the main source of federal funding for basic energy research, and for applied ERD&D.[33] For example, in 2007, DOE provided $2.5 billion for ERD&D (Gallagher 2008), while the combined ERD&D funding from USDA, USGS and DARPA amounted to $76 million (EIA 2008c), or 3 percent of the total federal ERD&D expenditures. Funding for basic energy sciences research is completely centralized in DOE and amounted to $1.2 billion in 2008.

Given the prevalence of DOE in supporting ERD&D in the United States, the decline of ERD&D DOE funding observed over the past 30 years is particularly worrying (Figure 3). DOE's ERD&D funding reached a maximum of $6.1 billion 2000$ in 1978, a low of $1.3 billion in 1998, and it increased gradually to $2.5 billion in 2008, which is still a factor of 2.5 below the 1978 level. During this time U.S. GDP grew by a factor of 2.3 from $5.0 to $11.6 trillion in year 2000$ (USDOC 2008); thus, as a percentage of GDP, DOE ERD&D funding decreased very sharply – from 0.12 percent to 0.02 percent.

However, since the release of the PCAST report in 1997 the crucial role of the U.S. government in supporting ETI all the way from basic research, to technology demonstration and deployment has been emphasized by scholars and practitioners. Government involvement in the demonstration and early-deployment stages of technology innovation is critical to overcome the many barriers that prevent technologies from jumping from the R&D to large-scale deployment – a phenomenon known as "the valley of death." Naturally, private sector involvement in funding ETI is and should be more prevalent as technologies move through the phases of innovation (Brooks 1967), as private entities are the more direct

[33] Through their Basic Energy Sciences (BES) program, and through their Energy Efficiency and Renewable Energy (EERE), Electricity Delivery and Energy Reliability (EDER), Fossil Energy R&D, and Clean Coal Technology (CCT) programs, respectively.

beneficiaries of technology. It is therefore important for the government to involve private sector actors as much as possible in demonstration projects.

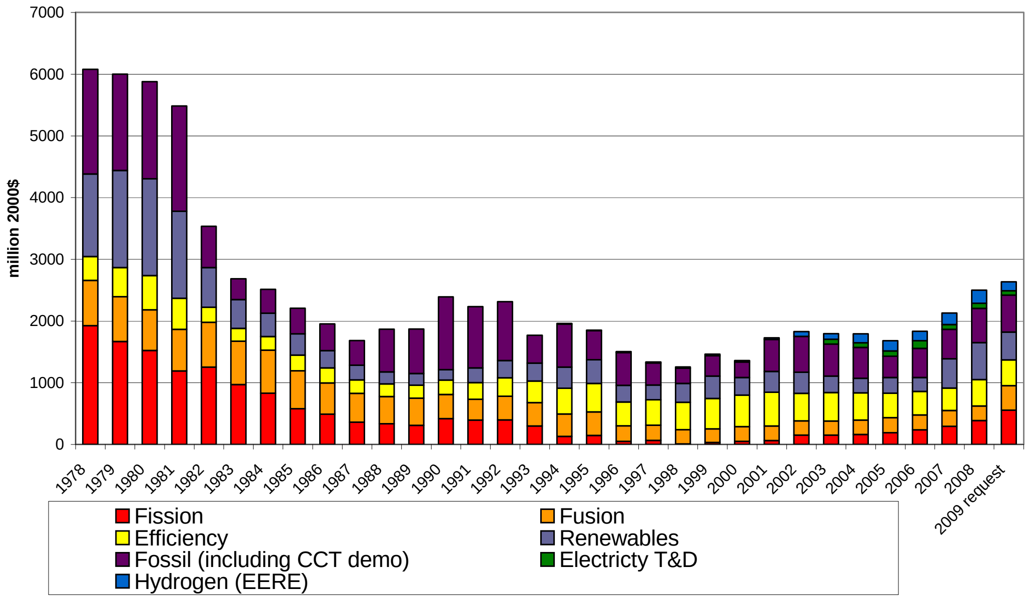

Figure 3: U.S. DOE energy RD&D spending from FY1978 to the FY2009 request in millions of 2000$ (Gallagher 2008).

The decline in public sector funding for ERD&D over the past 30 years is not unique to the United States, it is shared by all IEA Member countries with the exception of Japan (Runci 2005). But in spite of the fact that the United States is still the world's largest economy, the U.S. government is no longer investing the largest amount in ERD&D. In 2005 the United States was investing less than Japan and possibly less than the European Union in PPP-adjusted 2006$ (Figure 4).[34]

[34] It is worth noting that the data in Figure 4 are somewhat hard to interpret because Japan was investing two-thirds of its 2005 ERD&D budget in fission and fusion energy, and the United States was investing 42 percent of its budget in basic energy sciences, biological and environmental research (included in the "Other research" category.

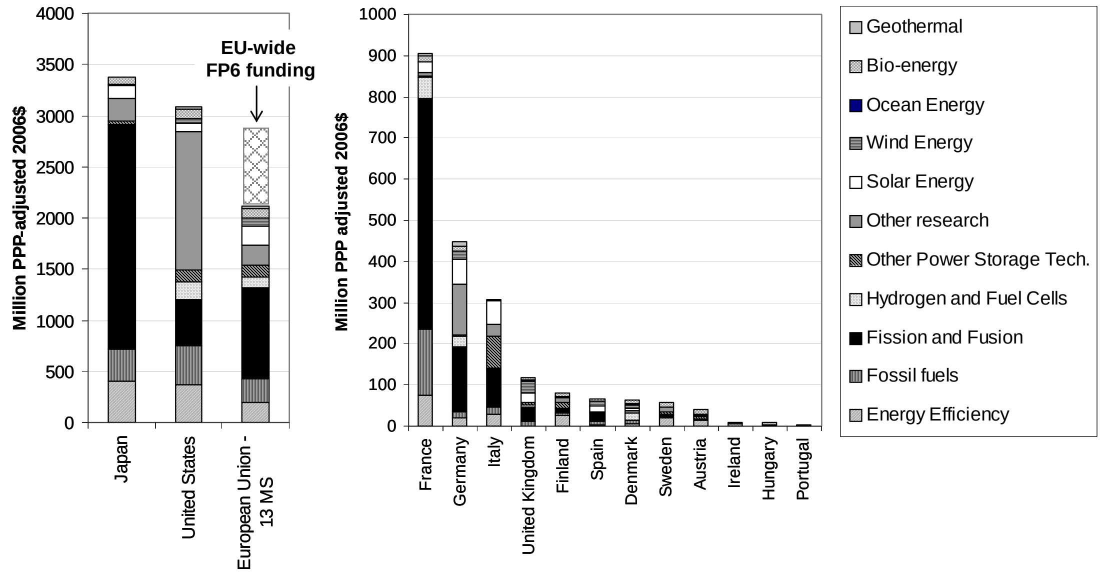

Figure 4: Reported 2005 public expenditures in ERD&D by 13 EU Member States (MS), Japan, and the United States in millions of PPP-adjusted 2006$ (IEA 2007a) and funding for energy R&D by the EU's Sixth Framework Programme for research, FP6 (EU 2007a).

The quantity and allocation of public ERD&D funding are not the only factors to look at when evaluating ERD&D expenditures, the effectiveness of the investments is critical. There have been two major studies focussed on effectiveness considerations. The first study was conducted by DOE in the year 2000 and it analyzed the benefits of 20 of its most successful energy efficiency and renewable energy programs (DOE 2000). Those twenty programs had saved the United States 5.8 EJ, or 6 percent of the energy it consumed in 2005 (IEA 2007b). These energy savings were three times greater than the total amount of funding for energy efficiency and renewable energy (EERE) appropriated by DOE. The second study was carried out by the National Research Council (NRC) and it evaluated DOE's fossil energy and energy efficiency programs between 1978 and 2000. The NRC found that the benefits of six energy efficiency programs,[35] which had been co-founded by the DOE and the private sector at a combined cost of $0.4 billion, added up to about $30 billion 2000$. These benefits significantly exceeded the $7.3 billion 2000$ spent by DOE on all energy efficiency programs between 1978 and 2000 (NRC 2001).[36] The NRC study also

[35] The six programs selected for detailed cost-benefit analysis were: advanced refrigerator/freezer compressors, electronic ballast for fluorescent lamps, low-emission glass, advanced lost foam casting, oxygen-fueled gas furnace, and advanced turbine systems. They included programs in the building technology, vehicle technology, and industry sub-programs.

[36] The economic return of $10.9 billion to the eight fossil energy programs assessed,[36] which had cost a total of $3.5 billion to DOE and private sector partners, were modest in comparison, and they did not allow the committee to claim that those eight programs had produced enough returns to cover the costs of the $15 billion invested by DOE over 22 years in fossil energy programs. These economic returns, however, did not

found that the combination of federal funding for ERD&D, financial incentives for adoption, and efficiency standards for buildings and equipment had been a major driver of the success of the efficiency programs (NRC 2001). The refrigerator (see Figure 5), the electronic ballast, and the low-emission window programs are examples of technologies which are widely used today thanks to a *virtuous cycle* by which RD&D successes allow the introduction of more stringent performance standards, and vice versa, standards encourage more RD&D successes. These case studies highlight the importance of designing *comprehensive policy packages*.

In the light of all of the above considerations, the past 10 years have seen a myriad of articles and reports from experts calling for a much larger and durable government effort in ERD&D funding, for better management of DOE projects, and for better planning.[37]

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include environmental and energy security benefits, which the NRC also estimated, or the knowledge benefits arising from the fact that some of the technologies developed within these DOE fossil energy programs might be of use in the future. Some examples of technology areas with knowledge benefits which might become useful in today's world of high oil prices are IGCC, oil shales, indirect coal liquefaction.

[37] Back in 1997 the PCAST report called from a doubling of DOE's basic sciences and ERD&D budget based on the challenges and opportunities of an accelerated ETI enterprise in the United States. Schock *et al.*
Robert N. Schock, William Fulkerson, Merwin L. Brown, Robert L. San Martin, David L. Greene, Jae Edmonds. 1999. How Much is Energy Research & Development Worth as Insurance? *Annual Review of Energy and Environment* 24:487-512.) estimated that the amount of public ER&D funding that would be needed to provide an insurance against the costs of climate change stabilization, oil price shocks, urban air pollution, and other energy disruptions was between $5-$7 billion (year 1999), which is more than double the amount currently spent today. In 2004 NCEP, which is a bipartisan group made up of senior figures from industry, academia, and the government, recommended a doubling of ERD&D expenditures over the period of 2005-2015
NCEP. 2004a. Ending the Energy Statemate. A Bipartisan Strategy to Meet America's Energy Challenges. *The National Commission on Energy Policy*:99.). This recommendation was reiterated in 2007 (
NCEP. 2007. Energy Policy Recommendations to the President and the 110th Congress. In *National Commission on Energy Policy*: The National Commission on Energy Policy.). Nemet & Kammen
Nemet, Gregory F., Kammen, Daniel M. 2007. U.S. energy research and development: Declining investment, increasing need, and the feasibility of expansion. *Energy Policy* 35:746-755.) compared the need for an expansion in public ERD&D with that of the Apollo and Manhattan projects, and call for an increase in ERD&D funding by a factor of 5-10. Ogden, Deutch and Podesta (
Ogden, Peter, Podesta, John, Deutch, John. 2008. A New Strategy to Spur Energy Innovation. *Issues in Science and Technology* (Winter).) recently called for at least a doubling of DOE's ERD&D budget.

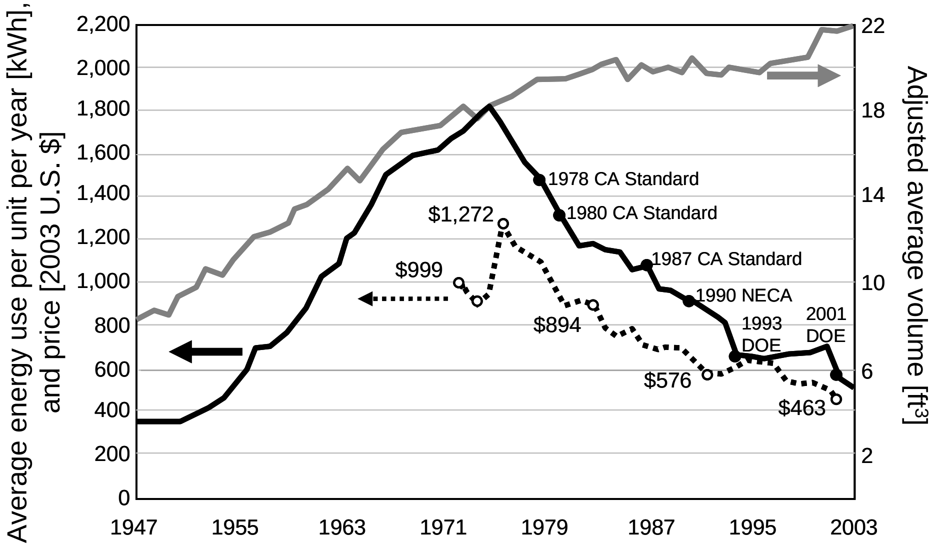

Figure 5: Evolution of annual electricity use (—), cost (---), and volume (—) of household refrigerator/freezers (Brown 2005; Geller 1999; Marilyn A. Brown 2005; NCEP 2004b).

4.1.2 Private sector

It has been estimated that the majority (two-thirds) of all R&D funding in the United States comes from the private sector (NSF 2007). Some recent estimates for the case of energy have suggested that the private sector only contributes between one third (Nemet 2007) and one half (Dooley 1999) of total US ER&D expenditures and that private-sector investments in this domain have fallen over the past two decades by something like a factor of four (Nemet 2007)[38]. Attempts to track private-sector ERD&D expenditures are notoriously difficult, however, plagued by lack of access to complete data as well as by ambiguities about what proportion of research on technologies that use energy – such as vehicles – should be classified as "energy research" (Gallagher et al 2006). Many in the energy industry argue that publicly available estimates of the private-sector's ERD&D are far too low and that assertions of a large real decline in recent decades are exaggerated. We take the range of possibilities for the private-sector's contribution to US ERD&D expenditures to be, in round numbers, between 1/3 and 2/3 of the total.

[38] The decrease in private sector ER&D funding recorded by Nemet and Kammen does not include funding from venture capital firms. Although in 2003 VC firms invested over $400 million in energy companies, Prudencio, Rodrigo. 2003. Nth Power 2003 Energy Venture Capital Study. *Nth Power LLC.*), which is approximately one third of the private sector ER&D investments, most of those funds are unlikely to have been channeled to ER&D.

Although this is a large uncertainty, even at the high end the ERD&D investments of the private sector can be easily judged to be inadequate, not only because it is low among virtually all high-tech industries as a proportion of revenues but, more tellingly, because the recent and current pace of advance is so clearly short of what the challenges require. Boosts in the incentives for private-sector RD&D in this domain are quite evidently warranted.

One might be tempted to think that the idea that both the private and the public sectors should ramp-up their ERD&D efforts simultaneously are in conflict with each other – that public ERD&D would "crowd-out" private investment – but recent analysis suggest that this is not the case. Public funding for R&D in the United States (David 1999) and in particular for energy R&D (Nemet 2007) does not appear to be substituting or "crowding-out" private sector investment. Hence, there is no clear indication that well-funded, well-run ERD&D DOE programs will do anything but help U.S. industries thrive in the energy business.

4.1.3 International cooperation

The importance of international cooperation in ERD&D arises from the various inherently global problems and opportunities of energy systems (PCAST 1999), e.g. energy-resource and energy-technology markets, nuclear proliferation, climate change, and providing access to modern energy to one third of humanity. The United States would benefit from cooperation because: cooperation on fundamental research with leading scientific groups from other countries does not involve IPR conflicts and has the potential to accelerate technical progress through knowledge sharing, at a reduced cost; cooperation on technology development with developing countries provides a learning opportunity for the United States to improve its products by adapting them to different conditions, creates beneficial scientific and business relationships with developing countries, and accelerates the expansion of the market for advanced energy technologies; and cooperation on particular technology areas, such as nuclear energy, is necessary to ensure that nuclear energy is safe and proliferation resistant (NCEP 2004a).

Recommendations

The decline in public and private ERD&D funding, increased international competition, observed returns to government ERD&D programs, and security, economic, and environmental challenges ahead call for a bold and coordinated U.S. ERD&D policy which should include the following actions:

- Increasing DOE's ERD&D budget by at least a factor of 2 in real terms, pushing DOE's ERD&D expenditures above $6 billion per year. This increased budget should be made reliable to allow project planning and continuity.
- Directing a large fraction of the budget increase to: public-private partnerships for technology-demonstration projects, technologies capable of dealing simultaneously with the three main challenges ahead, and those high-risk, high-payoff technologies that would not be funded by the private sector alone.
- Adopting a portfolio approach to investing in ERD&D projects including considerations regarding which technologies are likely to be substitutes or complements, the stage of technology development, the criticality of federal R&D investments to the probability of success of the projects, and measures of the potential benefits of each technology.[39] The portfolio approach should be used because it can account for the fact that the R&D enterprise is unpredictable, a single technology (or technology cluster) will not provide enough leverage against the challenges faced, and reliance on one solution is likely to create further problems.
- Strengthening the organizational structure and management procedures of DOE to effectively manage this expanded and more sophisticated federal ERD&D enterprise. It might even be necessary to create a complementary governmental institution to, for example, improve DOE's performance running demonstration projects.[40] Particular areas of improvement for DOE are: an increased communication between basic energy sciences and applied ERD&D programs; a better coordination between the activities of DOE and other agencies (in particular USDOC, USAID, and EPA); and a more systematic effort to improve and increase the number of relationships with industrial partners (Gallagher 2004; NCEP 2004a; NRC 2001).
- Increasing funding for basic energy sciences focussing on cross-cutting (integrative) research and novel concepts, and improving the coordination between ERD&D, basic

[39] An example of a methodology to evaluate the benefits of DOE programs was that developed by the NRC NRC. 2007. Prospective Evaluation of Applied Energy Research and Development at DOE (Phase Two). *The National Academies Press.*). The benefits considered were reductions of oil and natural gas imports, other economic benefits from cost reductions, and avoided CO_2 emissions. Other benefits that could be taken into account when planning ERD&D investments include: reduced emissions of other air pollutants, increased number of jobs, decreased water and land requirements, and increased resistance to terrorist threats.

[40] The Advanced Projects Research Agency for Energy (ARPA-E), modelled after DARPA, was authorized in 2007. Although it is not clear whether it will ever be functioning, the agency would serve to complement DOE's capacities. Ogden *et al.* proposed the creation of an independent organization, the Energy Technology Corporation to identify, coordinate and manage energy technology demonstration projects Ogden, Peter, Podesta, John, Deutch, John. 2008. A New Strategy to Spur Energy Innovation. *Issues in Science and Technology* (Winter).).

energy science research, and deployment policies (see Section 4.3) to speed up the innovation "pipeline" and reduce the barriers to the early deployment and widespread diffusion of new technologies.[41]

- Making R&D tax credits permanent.
- Increasing funding for international cooperation in fundamental research and applied ERD&D aimed by at least a factor of 3, and adopting a coherent international cooperation strategy. The United States should invest between $0.75 and $1 billion per year, and direct its funding both to fundamental research with countries that are advanced technologically, such as Japan and the European Union,[42] and to more applied research and demonstration projects in developing countries with rapidly expanding energy markets – China, India, Brazil, etc.

4.2. Education policy

Without educated people carrying out the ETI enterprise and making rational decisions regarding the acquisition and use of energy technologies, funds allocated to energy RD&D will not realize their potential benefits. In other words, the human "input" is essential to meet current and future energy challenges.

However, there are several indicators suggesting that the United States might not be doing a good job at creating the human resources it needs to be a competitive innovator in the energy-technology field. The "Rising Above the Gathering Storm" report from the National Academies of Sciences found that although the United States still excels in higher education and training, and although U.S. scientists and engineers still lead the world in publishing results, other countries are "catching up" (NAS 2005). Some indicators of this trend are that most of the 40 percent increase in global publishing in science and engineering between 1988 and 2001 came from Japanese, Western European, and Asian emerging economies – U.S. publications have remained essentially constant since 1992 – and that in 2001 the U.S. trade balance for high-technology products became negative. In the area of

[41] Between 2005 and 2008 DOE's funding for coal and CCS RD&D has increased by 54 percent in real dollars. This increase in advanced coal RD&D funding coincided with the passing of the Energy Policy Act in 2005, which included a measure providing loan guarantees for the deployment of advanced coal technologies that can limit or capture CO_2 emissions. Although the effectiveness of the loan guarantee provision in accelerating the deployment of advanced coal technologies has yet to be proven, the concept of increasing RD&D efforts and anticipating and reducing deployment barriers should be applied to other areas.

[42] An example of the type of projects that should be pursued with countries that are technologically advanced is the International Thermonuclear Experimental Reactor (ITER). ITER's project partners – the United States, Japan, the EU, China, India, and South Korea – are sharing the cost of developing fusion energy technologies, which could (in the very long term) radically change the world's energy system.

education, the increase of international competition in the fields of science and engineering poses challenges to the U.S. education system because of the comparative lack of preparation of K-12 education (as highlighted by PISA results[43]), there is a limited graduate interest in science and engineering majors, there is significant attrition among science and engineering undergraduate and graduate students,[44] and in some instances S&E education is inadequately preparing students to work outside universities. Most importantly, the NAS report identified the importance of optimizing its science and engineering human resources to respond to the nation's need for clean, reliable and affordable energy and to create high-quality jobs for Americans.

Recommendations

Many of the education-related recommendations of the "Rising Above the Gathering Storm" report, which are summarized below, are essential to accelerate ETI and ensure the sufficient size and continuity of the ETI enterprise.

- Improving K-12 science and mathematics education by: recruiting more science and mathematics teachers; strengthening the skills of science and mathematics teachers by supporting continuing education in the form of summer institutes, master's programs, and other types of training; and creating a voluntary national world-class curriculum.
- Encouraging high-school students to pursue science and engineering undergraduate degrees, and encouraging undergraduate and graduate students to pursue careers science and engineering research by: awarding 4-year scholarships for students pursuing undergraduate degrees in the physical and life sciences, engineering and mathematics; increasing the number of graduate fellowships for U.S. citizens in "areas of national

[43] The 2006 PISA (Program for International Student Assessment) data collection effort found that American 15-year-olds had average science and mathematics literacy scores below the average of all OECD countries and below some non-OECD countries
PISA. 2007. Highlights from PISA 2006: Performance of U.S. 15-Year-Old Students in Science and Mathematics Literacy and in an International Context. *U.S. Department of Education. National Center for Education Statistics.*. PISA is sponsored by the OECD, and assesses the reading, science, and mathematics literacy of 15 year-olds in 57 jurisdictions, 30 of which were OECD jurisdictions, and 27 of which were not. Unlike other tests, the PISA assessments measure application of knowledge, rather than curricular outcomes, and are thus useful to make comparisons across countries.
[44] In 2002 science, technology, engineering and mathematics degrees accounted for 17 percent of all first university degrees awarded, compared to an international average of 26 percent
Kuenzi, Jeffrey K. 2008. Science, Technology, Engineering, and Mathematics (STEM) Education: Background, Federal Policy, and Legislative Action. *Congressional Research Service*.

need;" and increasing the number of grants for outstanding early-career science and engineering scholars.

- Ensuring that the United States remains the most attractive place in which to study and perform research by, amongst other things, improving the visa process for international students and scholars.

The 2007 "America COMPETES," "10,000 Teachers, 10 Million Minds," and "Sewing the Seeds Through Science and Engineering" Acts authorized many of the above recommendations. It is now essential to ensure that initiatives are sufficiently funded, progress is monitored, and feedback is being used effectively to improve the programs.

4.3. Deployment policy

The energy challenges will not be addressed unless new energy technologies are deployed at a large scale. It follows that market-pull policies are necessary complements to the technology-push policies discussed until now, and that there should be coordination between both efforts to avoid wasting resources.

Once the technical feasibility of an energy technology has been demonstrated at scale, there might still be barriers preventing the technology from competing in the marketplace and achieving the necessary large-scale deployment. These barriers have been categorized as cost-effectiveness, fiscal, regulatory, statutory, intellectual property, and other barriers (e.g. information and policy uncertainty) (Brown 2007). Deployment policies are aimed at overcoming these barriers, and their nature is as varied as the barriers they are aiming to overcome. It is therefore very difficult to obtain an accurate picture of energy-technology deployment policies in the United States, especially when one takes into account the fact that states also have their own deployment incentives. Nonetheless, it is useful to review federal incentives aimed at dealing with cost-effectiveness barriers—the most pervasive ones according to the analysis from the Oak Ridge National Laboratory (Brown 2007)—because effectiveness considerations require that the federal government ultimately be in charge of adopting a coordinated energy-technology strategy in basic research, RD&D, and deployment.

The U.S. Energy Information Administration (EIA) categorized federal subsidies to energy markets into RD&D expenditures, and deployment expenditures, which can be divided into direct expenditures, tax-related subsidies, and financial support (EIA 2008c). In 2007 the largest subsidies for electricity production were being directed to electricity from

refined coal[45] (\$29.8/MWh), followed by wind (\$24.3/MWh), solar (\$23.4/MWh), nuclear (\$1.6/MWh) and landfill gas (\$1.4/MWh). The largest energy subsidies per million Btu unrelated to electricity production were being directed to biofuels (\$5.7/million Btu), solar energy (\$2.8/million Btu), and refined coal (\$1.3/million Btu). A break down of the subsidies by category and energy source[46] (Figure 6) gives useful insights regarding the role of large deployment subsidies in getting advanced energy technologies off the shelf. Tax-related subsidies dominate, in terms of size of the expenditures, but most importantly, the largest deployment subsidies are not targeted enough to buy-down the costs advanced technologies or help them reach the tipping point into widespread diffusion. Specifically:

- The largest subsidy (\$3 billion) was the Volumetric Ethanol Excise Tax (VEET) credit. VEET has been identified as highly ineffective because the cost of this subsidy in 2006 exceeded \$1,700 per ton of CO_2 avoided and \$85 per barrel of oil replaced (Metcalf 2008).[47]
- The second largest subsidy was the \$2.4 billion spent in refined coal electricity from the Alternative Fuel Production Tax Credit. This tax credit expires at the end of 2009 and was not targeted to promote the deployment of advanced coal technologies.
- With a value of \$0.9 billion and \$0.8 billion, the "expensing of exploration and development costs," and the "excess of percentage over cost depletion" tax expenditures were the third and fourth largest expenditures, respectively. Both of them fall into the oil and gas category and are more effective at encouraging an increase in domestic oil production than stimulating the deployment advanced technologies.
- The fifth largest expenditure (\$0.7 billion) was the New Technology Credit (also known as production tax credit, or PTC) for wind power. The wind PTC went into effect in 1994 and since its introduction overall wind capacity in the United States has grown from 2 GW to 17 GW in spite of the 1999, 2001, and 2003 PTC expirations, which led to 3 to 7 fold drops in yearly capacity additions on the subsequent years (AWEA 2007).

[45] The IRS defines synthetic fuels as coal that has undergone a refining process which has produced a "significant chemical change" – condition which is satisfied by spraying coal with things like limestone, acid, diesel, or other substances. Until December 31st 2007 synfuels qualified as "refined coal" provided the facility was placed in service before June 30th 1998. The definition of "refined coal" was revised in the American Jobs Creation Act of 2004. The new definition is that it is a gaseous, liquid or solid synthetic fuel derived from coal sold by the taxpayer with the expectation that it will be used to produce steam, certified as resulting in a qualified emission reduction, and produced in such a manner as to result in a product with a market value 50 percent greater than that of coal excluding increases caused by the materias added during the production.

[46] Note that this excludes \$1.9 billion in subsidies to energy efficiency programs in the industrial, transportation and residential sectors, and \$1.0 billion to improve transmission and distribution.

[47] This criticism does not imply that the VEET has had no effect in bringing about private sector investments in biofuels, but rather that it would be more effective if it was more targeted.

The U.S. experience with wind PTC illustrates its effectiveness promoting wind deployment, and the importance of predictable policies to encourage private sector investment.

One of the few reliable data sources of product-specific information combining public and private expenditures in RD&D, deployment subsidies, installed capacities, and changes in unit costs, is the case of PV systems in Japan (Watanabe 2000).[48] In a seminal paper, Grübler *et al*. used the Japanese PV story to show that reductions in unit costs are a function of both RD&D and deployment and commercialization investments, i.e. of suppliers and users of technology (Figure 7) (Grübler 1999). Hence, a very important consideration for designing deployment policies is that the ETI system should be assessed as a whole.

[48] The Japanese Ministry of Economy Trade and Industry (METI[48]) has funded PV RD&D programs since 1974.[48] A sharp increase in Japanese PV RD&D funding between 1979 and 1981, from ¥0.4 to ¥7 billion (in fixed 1985 prices), stimulated an increase in private sector PV RD&D investment from approximately ¥0.8 to ¥11.5 billion within about a year. METI's large increase in PV RD&D was accompanied by a PV cost buy-down program (a residential PV system dissemination subsidy) which was initiated in 1994 and administered through the New Energy Foundation (NEF). The size of the subsidy per system was gradually decreased—it was reduced by a factor of 7.5 between 1994 and 2001 and terminated in 2005 – while the total yearly subsidy increased from ¥2 billion in 1994 to ¥23.5 billion in 2001. The coordinated Japanese government action combining technology push and market pull reduced costs from ¥18,500/W in 1974 to ¥700/W in 2006 (both in year 2006¥) and it has turned Japan into a world leader in PV technology: after Germany Japan is the second largest country in terms of existing PV capacity (over 1.7 GW in 2006
Ikki, Osamu, Matsubara, Koji. 2007. National survey report of PV Power Applications in Japan 2006. *International Energy Agency*.); and three out of the top five PV cell manufacturers by production capacity[48] are Japanese
REN21. 2008. Renewables 2007: Global Status Report. *Renewable Energy Policy Network for the 21st Century* Deutsche Gesellschaft für Technische Zusammenarbeit (GTZ) GmbH.. But the Japanese PV story is one of determination and it is not over. In January 2008, the Japanese Prime Minister announced a new goal of increasing by a factor of 10 PV capacity in Japan by 2020 and by a factor of 40 by 2030. This involves ensuring that over 70 percent of newly built private buildings in Japan use solar energy
Fukuda, Yasuo. 2008. In pursuit of "Japan as a Low-carbon Society." Speech by H.E. Mr. Yasuo Fukuda, Prime Minister. *Japan Press Club* (June).).

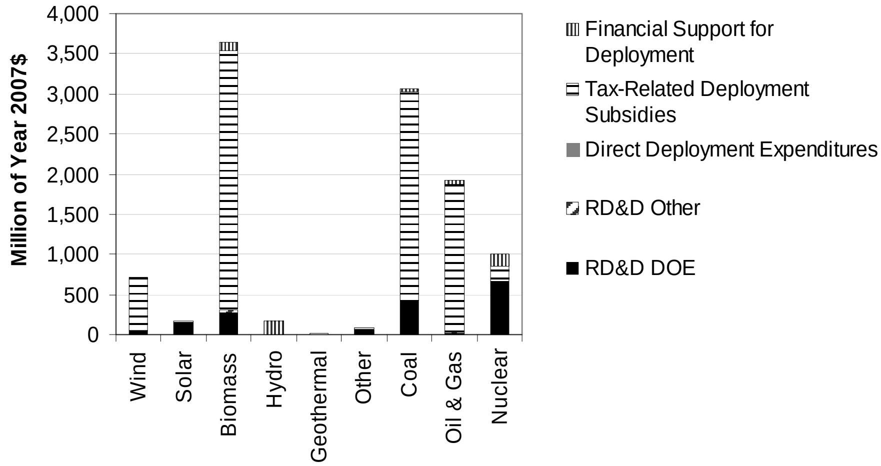

Figure 6: Direct funding for energy RD&D from DOE and other agencies (USDA and USGS), and deployment incentives (financial support, tax-related, and direct expenditures) for different energy sources in 2007. The "Other" category includes other renewable energy programs (e.g. landfill gas and international renewable energy program) and renewable energy program direction costs. Data from Gallagher *et al.* (Gallagher 2008) and EIA (EIA 2008c).

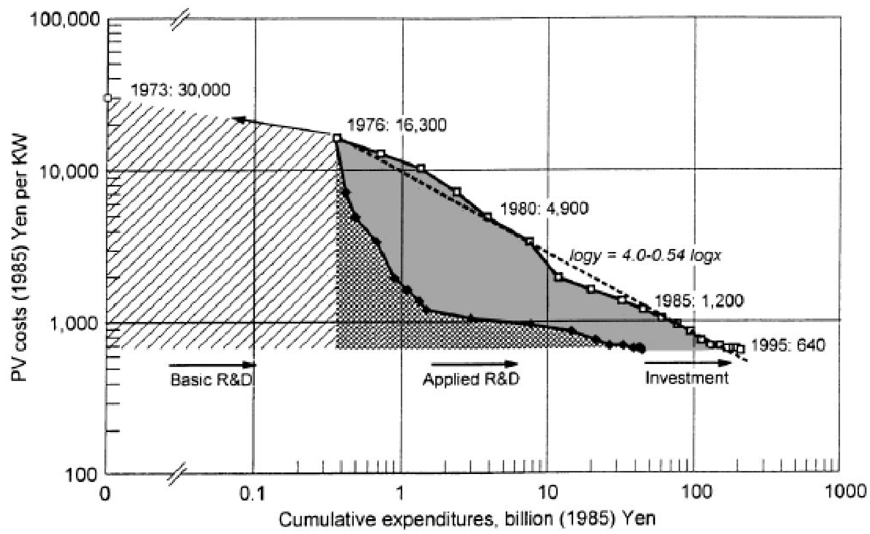

Figure 7: Modified learning curve for photovoltaic technologies in Japan between 1973 and 1995 portraying reductions in unit costs as a function of R&D and deployment investments from demonstration projects and commercial niche markets (Grübler 1999).

Recommendations

Below are some of the most urgent areas in which the U.S. government could make a difference by reducing significant barriers to the large-scale deployment of technologies that are relatively close to the market.[49]

- Providing investment certainty in the renewable energy arena by extending the eligibility of the PTC in five year periods, instead of one- or two-year periods.
- Enhancing the tax incentives for energy-efficiency investments in the Energy Policy Act of 2005.
- Directing greater resources to the commercialization of CCS, and ensuring that CCS is included in any tax-payer supported activity to develop coal-to-liquids technology.
- Redirecting resources currently devoted to energy subsidies which are not effectively targeted (e.g. VEET, and oil and gas tax credits) to programs that will promote the deployment of more promising options such as renewable power, cellulosic ethanol, clean high-quality diesel from organic waste, advanced nuclear waste disposal, more energy efficient technologies in the industrial, transportation, and buildings sector, and fossil power with CCS technologies.
- Providing targeted consumer and manufacturer incentives to encourage the domestic production, demonstration, and deployment of advanced automotive technologies.
- Addressing other barriers to the large-scale deployment of biofuels, including critical supporting infrastructures (gathering, distribution, and refuelling systems) and compatible vehicle technologies.

4.4. Standard-based policy

The United States has used two main types of standards: energy efficiency (performance) standards, and renewable portfolio standards (RPS).

Energy efficiency standards clearly increase the average efficiency of equipment. Although it has been argued that it is not clear whether performance standards are able to stimulate improvements over the existing most efficient technologies, and whether the same outcomes could have been reached at lower costs using market-based approaches, such as cap-and-trade systems, performance standards can be very effective because they force people and firms to access information and dispose of older technologies (Jaffe 2003).

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[49] Most of these recommendations come from the 2007 National Commission on Energy Policy report NCEP. 2007. Energy Policy Recommendations to the President and the 110th Congress. In *National Commission on Energy Policy*: The National Commission on Energy Policy.)

Corporate Average Fuel Efficiency (CAFE) standards have made, and will continue to make, the automobile fleet more fuel-efficient.[50] The coordination of RD&D programs, a series of more stringent standards, and the Super Efficient Refrigerator Program (SERP) have also resulted in dramatic increases in energy-efficiency and cost-effectiveness in refrigerators (Figure 5). Fluorescent lighting systems and more efficient clothes washers are other examples of technologies which achieved an accelerated deployment through a combination of RD&D and energy-efficiency standards (Hawkins 2001).

RPS policies establish numerical targets for renewable energy supply and impose them on retail electricity suppliers, which can generate or purchase electricity from renewable sources. They have been increasingly used to promote renewable energy generation at the state level since the late 1990s, and as of December 2007, 25 states and Washington D.C. had mandatory RPS policies (Figure 8).[51] Regarding their impact on ETI, well-designed RPS policies encourage competition amongst renewable energy developers to meet targets in the least-cost fashion, and reduce market and cost barriers, in the sense that an RPS policy gives certainty about the existence and size of the renewable energy market, and might accelerate the large-scale deployment of technologies which are still not cost-competitive. For example, in 2007 76 percent of all non-hydro installed renewable energy capacity additions in the United States took place in states with RPS policies.

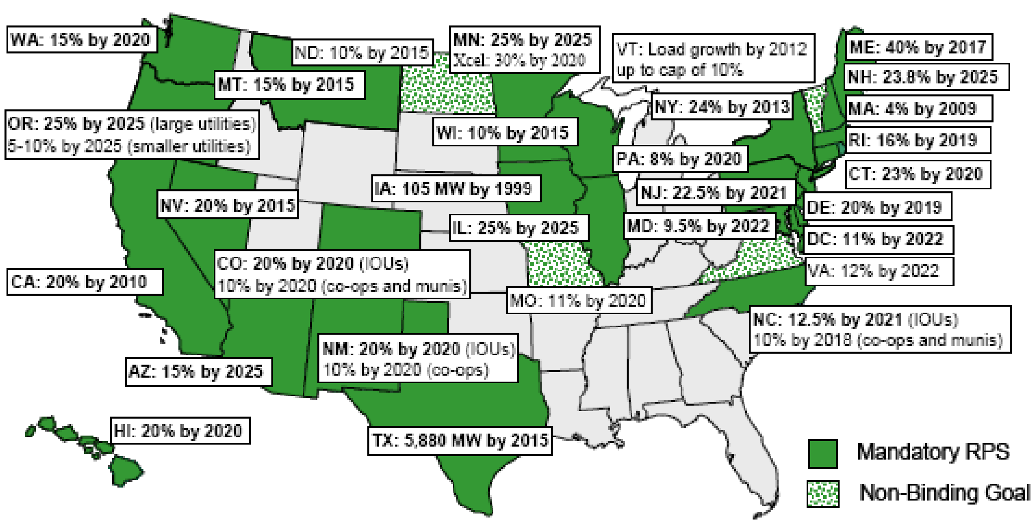

Figure 8: State RPS policies and non-binding renewable energy goals (Wiser 2008).

[50] The Energy Security and Independence Act of 2007 was the first federal statute to require an increase in fuel economy since 1975, calling for a CAFE of 35 miles per gallon by 2020 – a 40 percent increase in efficiency.
[51] Once all mandatory RPS programs are implemented they will apply to the entities supplying 46 percent of the retail electricity sales in the United States
Wiser, Ryan, Barbose, Galen. 2008. Renewables Portfolio Standards in the United States. A Status Report with Data Through 2007. *Lawrence Berkeley National Laboratory.*

Recommendations

The standard-based policies listed below will complement the policy package to accelerate the deployment of more advanced energy technologies.

- Improving heavy-truck fuel economy standards and adopting efficiency standards for light-duty vehicle replacement tires.
- Ensuring that DOE follows through on its commitment to issue new standards for more than 30 residential appliances and commercial equipment between 2006 and 2011.[52]
- Adopting a federal RPS to increase the share of renewable electricity to at least 15 percent by 2020.
- Expanding the use the Energy Star model of symbols and information campaigns to influence consumer behavior in the purchase of energy-efficient vehicles and building materials, and homes.[53]

4.5. Climate policy: a market-based program to limit GHG emissions

A well-designed, long-term and predictable climate regulation – either a cap-and-trade system or a tax – would minimize the market-wide abatement cost of achieving GHG emission reductions targets. Because firms would have flexibility regarding how much they emit, the reductions achieved would be those that are the least expensive. In addition, such a regulation would send important price signals that would incentivize firms to invest in the development and deployment of low-carbon technologies (Stavins 2007).

However, by itself, even a well-designed climate regulation will not be able stimulate all the ETI that is needed, because of the market failures associated with the R&D enterprise (e.g. knowledge spillovers).[54] Furthermore, any near-term market-based climate regulation will be insufficient (on its own) to overcome the barriers to the deployment of important GHG mitigation technologies, such as CCS (NCEP 2007), because the political process required to reach agreement on climate legislation will not result in sufficiently high allowance prices or taxes. As a result, it is essential to coordinate an aggressive program to

[52] As of November 2007 it had adopted new standards for two appliances
DOE. 2007. DOE Increases Energy Efficiency Standards for Residential Furnaces & Boilers. *U.S. Department of Energy.*.

[53] This action should be complemented by encouraging publicity efforts of active local program sponsors, as it has been shown that such efforts increase recognition, understanding, and influence of the label
EPA. 2008. National Awareness of ENERGY STAR for 2007: Analysis of 2007 CEE Household Survey. *EPA Office of Air and Radiation.*).

[54] Equally, ERD&D alone need not result in GHG without climate change policies limiting emissions
Edmonds, Jae, Clarke, John, Dooley, James, Kim, Son H., Smith, Stephen J. 2004. Stabilization of CO2 in a B2 world: insights on the roles of carbon capture and disposal, hydrogen, and transportation technologies. *Energy Economics* 26:517-537..

limit GHG emissions with the other ETI policies that have been discussed, i.e. ERD&D, education, deployment, and standard-based policies.

Recommendations

The United States must pass as soon as possible a mandatory economy-wide GHG emissions regulation, starting with CO_2,[55] using emissions limits (or taxes) that will become more stringent (or larger) with time. Short-term limits should be aimed at achieving at least a 15 percent reduction of GHG emissions over 2006 levels by 2030, and at least a 60 percent below 1990 levels by 2050. The country and the world cannot afford to wait for "the perfect" emissions regulation for all stakeholders. Instead, the emissions regulations should have built-in flexibilities to adapt to future economic, environmental, and technological information.

[55] State governments have also moved ahead of the federal government in this area. The Regional Greenhouse Gas Initiative (RGGI)—a cap-and-trade program which includes 10 Northeastern states – and the California Greenhouse Gas Solutions Act (AB32), are scheduled to begin cutting emissions in 2015 and 2012, respectively.

Nomenclature

Acronym	Name
ARPA-E	Advanced Research Projects Agency for Energy
AWEA	American Wind Energy Association
Btu	British thermal unit = 1055.1 Joules
CAFÉ	Corporate Average Fuel Economy
CCS	Carbon capture and storage
DARPA	Defense Advanced Research Projects Agency
DIW	Deutches Institut für Wirtschaftsforschung
DOE	U.S. Department of Energy
EIA	U.S. Energy Information Administration
EJ	Exajoules = 10^{18} Joules
EPA	Environmental Protection Agency
ERD&D	Energy Research, Development and Demonstration
ETI	Energy-Technology Innovation
ETS	Emissions Trading Scheme
EU	European Union
EWEA	European Wind Energy Association
HEV	Hybrid Electric Vehicle
IPCC	Intergovernmental Panel on Climate Change
IAEA	International Atomic Energy Agency
IEA	International Energy Agency
ITER	International Thermonuclear Experimental Reactor
GHG	Greenhouse gases
METI	Japanese Ministry of Economy, Trade and Industry
MITI	Japanese Ministry of International Trade and Industry
MWh	Megawatthour
NCEP	National Commission on Energy Policy
NEF	Japanese New Energy Foundation
NRC	National Research Council
NSB	National Science Board (provides oversight and policy guidance to the NSF)
NSF	National Science Foundation
OECD	Organization for Economic Cooperation and Development
PISA	Program for International Student Assessment

PNNL	Pacific Northwest National Laboratory
ppm	Parts per million
PPP	Purchase Power Parity
PTC	Production Tax Credit
PV	Photovoltaic
R&D	Research and Development
RD3	Research, Development, Demonstration, and Deployment
RPS	Renewable Portfolio Standards
SET-Plan	Strategic Energy Technology Plan
USDOC	U.S. Department of Commerce
USAID	U.S. Agency for International Development
USDA	U.S. Department of Agriculture
USGS	U.S. Geological Survey
USCB	United States Census Bureau
VEET	Volumetric Ethanol Excise Tax credit
WNA	World Nuclear Association

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